CONSTRUCTION SYSTEMS OF TIMBER STRUCTURES IN CHINA AND ITALY: A FIRST COMPARISON OF CONSERVATION APPROACHES

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Abstract.

Timber is one of the construction materials widely used in historical structures all over the world. Particularly in China, main historic building and architectural heritage is made of timber structure, the traditional system is a pure wooden framework, which two main ones are Tai-liang and Chuan-dou. They are composed by vertical columns that begin at ground level, short vertical supports as struts, and horizontal beams or lintels connecting the struts and columns. In Italy, instead, timber components, as floor and roof, are included in the building structural system, commonly made of masonry.

In the paper, the main aspects concerning the two construction systems are compared, in particular, the following categories are taken into account: Typologies of construction systems, are mainly demonstrated the framework in macroscopic way and other minor carpentry work in microscopic way; Composition of construction systems, which include main structural composition and method of elements' connection; With the great different and distant timber technical traditions between two countries, aiming at illustrating the basic requirement of conservation approaches.

The comparison among the various constructive systems between Italy and China, according to the analyzed aspects, constitutes a preliminary but fundamental step in the process of preservation of historical materials and structural behavior of timber components. It represents a crucial step for the reliability of investigation and experimental methods.

1 INTRODUCTION

To understand conservation approaches of traditional and historic timber constructions require the preliminary and fundamental knowledge of construction system. With the long history of Chinese and Italian timber structural architectures, both of them have developed a distinctive construction system to support the whole building.

From the perspective of configuration of the building, Chinese traditional architecture has developed a more notable character from configuration, is divided into 3 parts, the roof, the body and the base (Fig.1), the distinctive configuration generated on account of function, structure and artistic level, which are mutually combined. The wooden framework was adopted in traditional construction system, which contains the roof and body, is comprised of longitudinal column and transversal beam. The area of enclosed 4 columns make one “Jian”, the standard area of a room in traditional way, a building is composed by several “Jian”. The different way of overlapping and jointing on columns, beams and other elements generate two main frame systems in China, which is Tai-liang and Chuan-dou, which will be described in following context. The weight-bearing frame provides flexibility for the placement of walls, windows, and doors. Non-load-bearing walls can be made of many different materials, such as brick, clay, wood, bamboo, or even corn or cotton stalks.

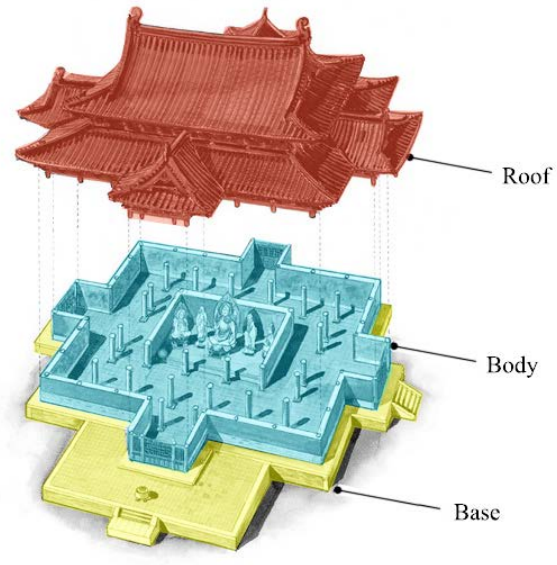


Figure 1: Configuration of Chinese ancient building

Compared with configuration of Italian building, the situation is too complex to make a typological conclusion, however the roof can be discussed, which the presumably of the simplest type is made of two inclined struts, king post and horizontal tie beam. Its distance covering from 5 to 15m, with the most basic prototype, it can be transformed into various complex types. Regardless of the basic simple truss and transformations, the composed truss, both of them are the most important structural part of the whole building.

2 TYPOLOGIES OF CONSTRUCTION SYSTEMS

2.1 Framework based upon roof

Following the Chinese traditional timber categorization methodology, namely the “major carpentry” viewpoint which is based upon the structural techniques of the roof, are divided

into two main types: “Tai-liang” and “Chuan-dou” structure. The difference between these two kinds of framework is specifically the way of connection between the beam (lintel) and columns (Fig.2). Tai-liang means there is a big beam between two peristyle columns, on which another beam support purlin, the horizontal elements that support the rafters, are positioned along the stepped shoulders of the skeleton, such as The Hall of Supreme Harmony (Taihedian) at the center of the Forbidden City in Beijing (Fig.3). The second type of structure is “Chuan-dou”. In this kind of structure, the entire skeleton of the building consisted of columns, purlins, struts, lintels. The purlins are located on the top of the columns or struts, which are connected by the horizontal lintels and architraves. A typical example is the traditional dwellings in Southern China (Fig.4). Tai-liang was mostly built in North area of China, especially prevalent applied in the official or royal building. And Chuan-dou is usually built in South area of China, and because of climate, it tends to be more ventilated and lighter. In addition to the two main types illustrated above, there is another type, Jing-gan. In this technique, wall could be obtained by using rows of logs placed horizontally and without column and beam structures. The construction systems can be met diverse requirements of building types, ranging from royal palace, temple, dwelling, garden building to tower and bridge. The existing typical cases, such as the great hall of Foguang temple, Wutai mountain, in Shanxi; Guanyinge of Dule temple, in Jixian, Tianjin; wood pagoda, in Ying xian of Shanxi, etc. As well as Ling’en Palace, Chang Tomb of Emperor Yongle, the biggest palace hall in China ancient time, whose area is nearly 2,000 m^2.

Dong drum tower, is one of most important and charismatic public buildings in the architecture of Chinese Dong minority, the existing drum tower were mostly built from early Qing dynasty to fairly recent years[1]. Timber is the unique material used in constructing the Dong drum towers, furthermore, it contains both Tai-liang and Chuan-dou types. Taking Yan Lan drum tower as an example, is a typical Tai-liang drum tower (Fig.5), which was erected in A.D. 1764(Qing Dynasty) in Yan Lan village, Tongdao county of Hunan province. What’s more, it is combined with another auxiliary building such as village gate and temple, thus forming a complex with special shapes along with a variable public space within the village.

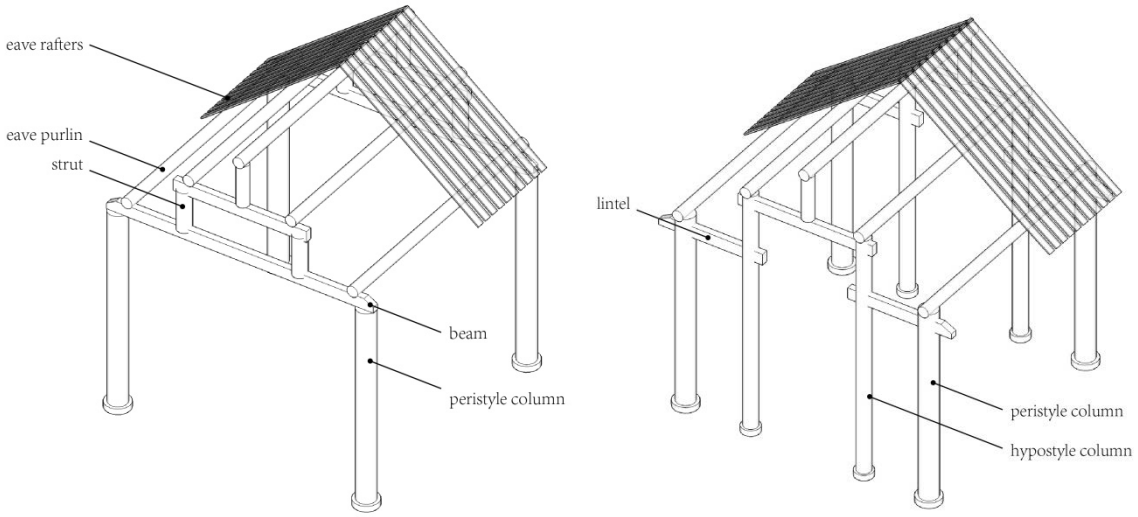


Figure 2: Tai-liang(the left one) and Chuan-dou(the right one) structure

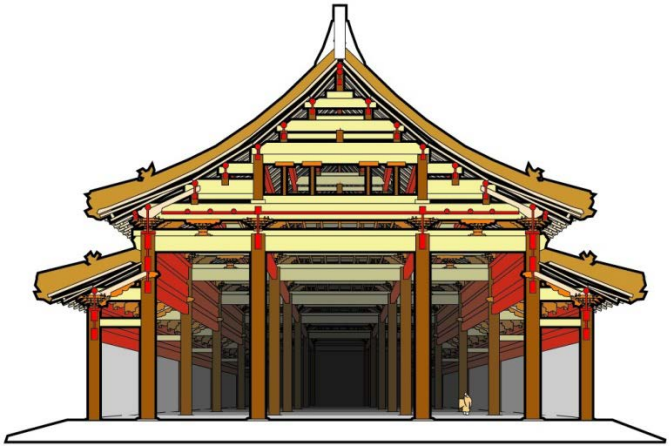
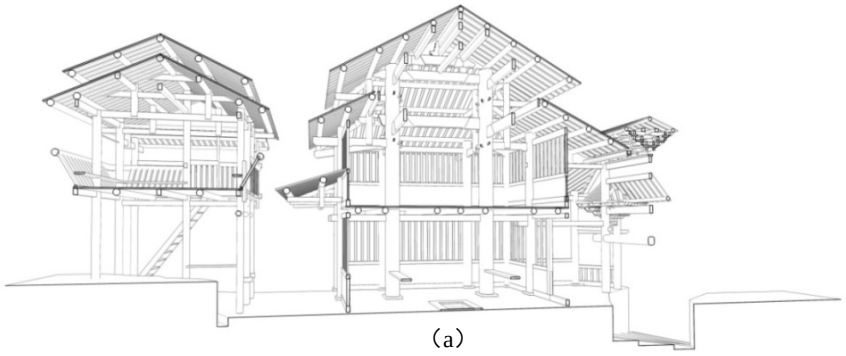


Figure 3: The Hall of Supreme Harmony (Taihedian) in Beijing, China (A.D. 1695)[1]

Figure 4: Traditional dwelling, Fujian, China[2]

Chuan-dou applied in Dong drum tower exiting a subtle difference with Han nationality's official one, the plan of Chuan-dou drum towers are usually a regular polygon. There is a central post (touching ground) or a king post (suspended above the ground) being located in the geometric center of a regular polygonal plane, rising up to the top. Using this kind of construction technique, the roof style of drum tower is multi-eave pyramidal roof makes the style is symbol of Dong minority. The Dong Chuan-dou drum towers are generally more than five stories or eaves (Fig.6). The drum towers take full advantage of this type of construction by expressing the creativeness and development of the traditional timber structure of China.

[1] Re-drawn from http://chounamoul.exblog.jp/15878540/
[2] From Qianlang Li. 2009. *Through the Wall*. Guangxi Normal University Press, Naning, China.



（a）

(b)

Figure 5: Yang lan drum tower

(a) 3D model；(b) Appearance

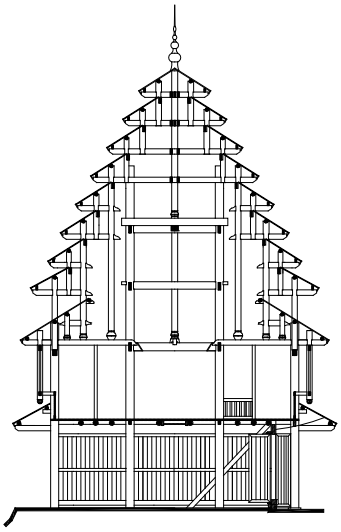


Figure 6: Gao sheng drum tower

On the other hand, there are so many kinds of roof structures in Italy that the precise classification on typology of roof cannot be concluded directly, however the most common one is a triangle truss composed by a horizontal beam, on which a vertical king post and two inclined struts connected both beam and king post with iron ties (Fig.7). Others can be regarded as the transformations, such as hammer beam truss, or even a structure with only rafters and inclined beam. There are two UNESCO Word heritages in Italy, i.e. Basilica of St. Apollinare in Classe (Fig.8), Ravenna, Emilia-Romagna Region, was erected in beginning of 6th century, another one is Patriarchal Basilica of Aquileia (Fig.9), Aquileia, Udine, Friuli-Venezia Giulia

Region, which was erected in A.D.1031, then rebuilt in A.D.1379. Both are covered by a timber structural roof, despite the diverse types of construction techniques.

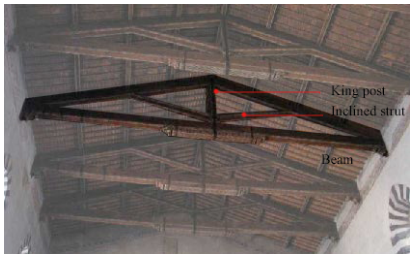


Figure 7: Simple truss (prototype)

Figure 8: Basilica of St. Apollinare in Classe [3]

Figure 9: Patriarchal Basilica of Aquileia[4]

Some significant examples can be found in Veneto region, as follows.

The "Arsenale" of Venice in Italy, is a complex of former shipyards and armories. It transformed more and more complex from years to years. The building complex under consideration is formed by the roofs, very simple timber trusses at the beginning (first half of the 14th century), large span, huge and complex spatial timber structures during 16th century, engineered mixed steel-timber and steel trusses in the second half of the 19th century [2]. The most original and simple type of truss indicates in this paper was constructed in "Corderie" and "Isolotto" (Fig. 10, 11). The examples characterize the structural technique that widely used in the roof constructions.

In the case of San Fermo, a XI century's church located in Verona of Italy. The wooden roof is a distinctive structure that composed by a large series of struts and puddled iron ties, which is one of the types of structures with complex truss, to be more precisely, the hammer beam truss (Fig.12). The roof is a composition of many timber beams with a large series of elements like struts, decorative parts, puddled iron ties and many other connection devices, it is a sort of arch-braced structure, then the vertical load force upon the lateral walls of the church. It's an open truss with a span of 18m that not far from the widest one of Westminster Hall [3]. After analyzing above, utilizing hammer beam truss may widen the span the truss.

Both of Tai-liang and Chuan-dou are mortised mutually by horizontal and vertical structural elements, the load is transmitted upward through struts and beams to the top of roof, then the gravitational forces downward out through from the framework to the ground. Thus, a circulatory construction system is generated. Therefore, the elements consume the seismic energy to insulate and reduce the vibration by their interaction. According to the theory of modern vibration control [4], the construction system is a passive reduce-seismic system. Compared with the construction system of China, Italy also using a distinctive system that timber com-

[3] From https://arsartisticadventureofmankind.wordpress.com/2014/10/24/golden-age-of-byzantine-art-iii-churches-of-ravenna-santapollinare-nuovo-santapollinare-in-classe-and-san-vitale/
[4] From https://en.wikipedia.org/wiki/Aquileia

ponents included in the structural system of masonry constructions. The timber structure is not the only material of the construction system, but it still plays an important structural role.

Figure 10: "Corderie" Truss[5]

Figure 11: "Isolotto" Truss[6]

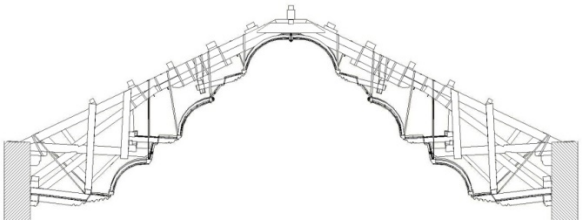


Figure 12: The wooden roof- San Fermo

2.2 Other typologies: minor carpentry work

In addition to the framework, there still are other minor carpentry works, including door, window, ceiling, caisson, floor, etc.

The door and window in China may be classified into one unit, because both of them utilizing the similar method of work, which is made of frame and casement. And the method of work on door and window is different depending on different level of architectures. The "Jian-chuang (balustrade window and door)" (Fig.13) is used in high level or significant architecture, like royal temple. The "Zhi-zhai (removable window and door)" (Fig.14) is used in secondary architectures, like folk dwellings.

The carpentry method of caisson in China and Italy is similar, is made of grid shape structure by wooden kneel, on which is a ceiling. Chinese caisson tends to be decorated in more palatial way (Fig.15[7], 16[8]).

Figure 13: Jian-chuang

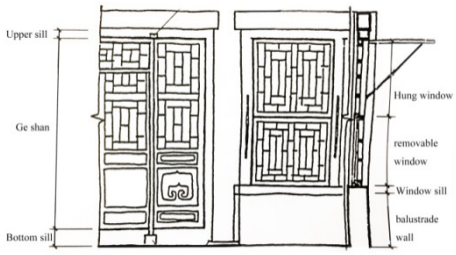


Figure 14: Zhi-zhai

[5] From http://www.artmoorhouse.com/artists/antonio-martinelli-gallery.php

[6] From http://www.artribune.com/attualita/2015/05/biennale-di-venezia-il-padiglione-dellamerica-latina-raccontato-da-alfons-hug/

[7] http://tiscsvr.tbroc.gov.tw/photo.asp?phrfnbr=11205

[8] From the PowerPoint "La diagnosi delle strutture lignee in opera: criteri, mezzi, operatività" of Massimo MANNUCCI. Pp23.

Figure 15: Caisson in China

Figure 16: Caisson in Italy

3 COMPOSITION OF CONSTRUCTION SYSTEMS

3.1 Main structural elements

There are tremendous variety of structural elements, the most typical and primary are concerning below.

3.1.1 Column or strut

Wooden column in China is classified into peristyle columns, hypostyle columns and central column, what's more, the strut is another kind of column, is post on the beam rather than touching ground, the structural function is similar with column. The columns depicted in following Figure.

3.1.2 Beam or lintel

Beam and lintel both are the transverse elements, is support on the column or wall along the direction of span. And lintel is inserting into the column rather than posting on it, on which are the struts.

3.1.3 Braced-arch

Wooden braced-arch is an arch of timber, having a truss-like framework maintaining rigidity under a variety of loads, such as Palazzo della ragione, in Padova of Italy (Fig.17).

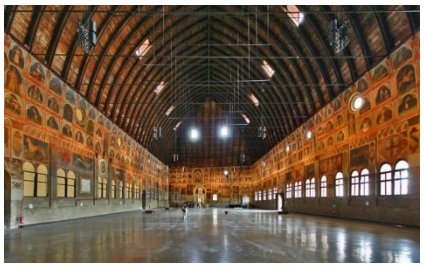


Figure 17: Indoors view of Palazzo della ragione

3.1.4 Tou-kung

Tou-kung is a distinctive structure in Chinese traditional building, in simple terms is a series of brackets and blocks broken from a whole into hundreds of smaller components and used joints to produce a larger component. This system allow for the distribution of forces and transmission of weight across the joints [5]. It is used to stand on the column and support the roof tier. Due to the different position of Tou-kung, it has Zhu-tou ke (Tou-kung sets on columns), Ping-shen ke (Tou-kung sets between columns), Jiao ke (Tou-kung sets on the Corner) these three classification. Tou-kung is composed of Tou, Ang, Qiao, Sheng, Kung and some other elements (Fig.18).

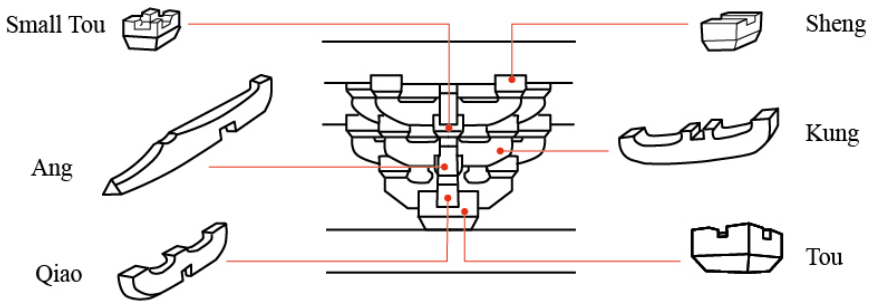


Figure 18: Constitution of Tou-Kung

3.2 Method of elements' connection

In China, the "Sun-mao" elements (tenon and mortise joints) were stared using in Hemudu Site for overhead timber structure six to seven thousand years ago. The main body of timber structure matured and additional forms of tenon and mortise joints were highly developed in Han dynasty. Along with the use of Sun-mao structures in Ming and Qing dynasties, over a thousand architectural forms of concise style present a liberal yet solemn air. The largest timber structure architecture first built in Ming Dynasty in China, the Forbidden City.

The most basic mortise and tenon comprises two components: the mortise hole and the tenon tongue, is a mean of joining two pieces of woodworking at an angle (usually 90°) to each other. There are still many joint variations based on the simplest one (Fig.19).

The tenon and mortise in Italy is different. Rather than using the timber as a unique material, glue is used to secure the pieces together and variations on the joint. The clamping wedge and bracket metal sealing is also common used to lock the joint in place (Fig.20).

It is not easy to check the inner structural connection from the outside of Sun-mao. Furthermore, tenon and mortise variations are highly-diverse from carpenters who hold different inherited techniques, therefore, analysis of traditional timber construction systems in scientific way requires not only the research of specific nodes, but also the acquaintance and comparison of various tenon and mortise craft-working, even the cultural diversity between East Asia and Europe [6].

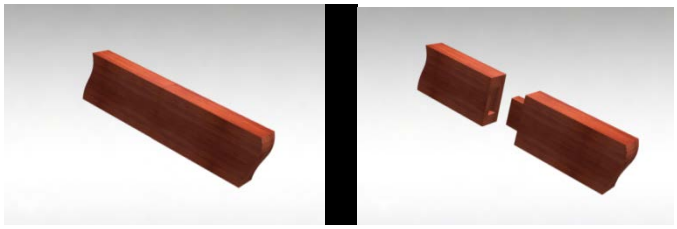


Figure 19: "Sun-mao" (tenon and mortise joint)

Figure 20: Tenon and mortise (Castello Estense, Ferrara, Italy)

4 CONSERVATION APPROACHES AND PRINCEPLES

The part aimed at defining basic and universally applicable principles and practices for the conservation of historic timber structures with due respect to their cultural significance [7]. However, due to the status that there are as great different in timber construction systems as there are species of trees, differences in climate and contrasts of terrain as well as the conservation legislation system between China and Italy.

For example, the repair and maintenance of Chinese ancient buildings must be followed the principle of the availability of historic building of original condition, which refers to the all the historical significance of heritages in individual or complex architectures. No.2.0.2 of Chinese national code [8] read the content should be preserved when conservation and restoration implements:

1. The original architectural form, which includes the layout of plan, facade, construction character and aesthetic context;

2. The original architectural structure;

3. The original architectural material;

4. The original traditional method.

The original condition not only includes the condition prior to any conservation interventions but also the condition after having been subjected to treatments, adaptations, or reconstructions during the course of its history and which interventions are judged to have significance, including a ruined state that reveals important historical attributes. In complex situations, scientific investigation should be undertaken to determine the historic condition. When a historic building preserves fabric or techniques from several periods, the values should be identified and conserved so that all the elements of significance are retained.

In a word, the primary aim of conservation is to maintain the historical authenticity and integrity of the cultural heritage. Traditional and ancient timber constructions refer to all types of building regardless of they are wholly or partially in timber that have cultural significance, for the purpose of conservation of these structures, the principles [7]:

Take into account the great diversity of historic timber structures; take into account the various species and qualities of wood used to build them; recognize the vulnerability of structures wholly or partially in timber due to material decay and degradation in varying environmental and climatic conditions, caused by humidity fluctuations, light, fungal and insect attacks, wear and tear, fire and other disasters; note the Venice Charter, the Burra Charter and related UNESCO and ICOMOS doctrine, and seek to apply these general principles to the protection and preservation of historic timber structures.

Refers to the each procedures, are as following,

1. Inspection and diagnosis

The state of historic construction and its surrounding environment ought to be recorded and analyzed carefully before any intervention, aiming to acquire and catalogue the historical information, including traditional carpentry skill or characteristic samples of structures as well as the materials used in previously treatments. In accordance with the Article 16 of Venice Charter [9]and the ICOMOS Principles for the Recording of Monuments Groups of Buildings and Sites [10]. A thorough and accurate diagnosis of the condition and the causes of decay and structural failure of the timber structure should precede any intervention.

2. Monitoring and maintenance

A regular monitoring and maintenance is vital to conservation of historic timber buildings. It can find and manage the problem timely and prompt, for the purpose of earliest and minimum intervention to the historic building or cultural heritage. Skilled technicians and profes-

sional device is the important method. Rather than the most advanced device, the optimum and suitable method should be adopted [11].

3. Intervention

Any proposed intervention should follow traditional means and be reversible, if technically possible, or at least not prejudice or impede future preservation work whenever this may become necessary; and not hinder the possibility of later access to evidence incorporated in the structure. And the historic structure should be considered as a whole, including structural members.

4. Repairing and replacement

New members or parts of members should be made of the same species of wood with the same, or, if appropriate, with better, grading as in the members being replaced. Where possible, this should also include similar natural characteristics. The moisture content and other physical characteristics of the replacement timber should be compatible with the existing structure. Craftsmanship and construction technology, including the use of dressing tools or machinery, should, where possible, correspond with those used originally.

5. Contemporary and materials and technologies

Contemporary materials should be chosen and used with the greatest caution, and only in cases where the durability and structural behavior of the materials and construction techniques have been tested in advance and satisfactorily proven over a sufficiently long period of time.

5 CONCLUSIONS

Due to the primary state of the research on comparison of construction systems, the conclusions are still under a qualitative stage. Therefore, the conclusions below are the general comparison in most common situation.

1. Timber structural position, which is the biggest difference between China and Italy, the former one is built in the whole timber structural framework meanwhile it is a load-bearing system itself, conversely, in most situation, the main timber structure only built in roof or floor and as a part of the whole building for the latter one.

2. Main typology of framework based on roof in China, from ancient time to nowadays, however, in any case, there were built in Tai-liang and Chuan-dou. Compared with Italian one, the typology was unidentified yet, the classification cannot be defined precisely. However the most basic and common one is the simple truss composed by king post, inclined struts and tie beam. Others are the transformation based on it. Rather than there are mainly horizontal and vertical elements in Tai-ling and Chuan-dou, the braced arch is common used in Italian building, etc. That makes the span of building more flexible than Chinese one, for example, to reach the same span of building, Tai-liang or Chuan-dou takes more woods than the construction with braced arch.

3. There are other typologies of the construction system in microscopic way. Door & window is another complicated carpentry work in China; The method of caisson is different between China and Italy, which the Chinese one possesses a more complex-structure than Italian one, as well as the aesthetic expression; In most situation, floors and some balconies within the buildings are built in wooden structure in Italy.

4. The tenon-mortise joints between these two countries are totally independent system, refers to the connection way or even structural behavior [6] is different. However the comparison can make the knowledge of timber structure more clear and integrated.

5. Considering the differences background of China and Italy, however an essential requirement in the conservation of a historic building or cultural heritage is to preserve its values, authenticity and integrity as they have evolved during the course of its history. Through

good conservation practice, a site's historic and cultural context and its cultural traditions are preserved and retained for the future.

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